Assimilation of Three-Dimensional Phase-Resolved Wave-Field Data Using an Efficient High-Order Spectral Method

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LONG-TERM GOAL

The long-term goal is to develop a robust and efficient computational tool for direct phase-resolved large-scale simulations of nonlinear ocean wave-field evolutions under offshore and coastal environments including realistic effects due to nonlinear wave-wave interactions, variable current, wave-breaking dissipation, bottom reflection and refraction, and wind-wave interactions.

SCIENTIFIC OBJECTIVES:

The specific scientific objectives of this program are to:

- Extend and apply an existing phase-resolved simulation program, a powerful high-order spectral method (HOS) for nonlinear wave-wave interactions, to assimilate realistic ocean wave-field data and to predict long-time evolutions of such nonlinear wave-fields
- Obtain realizable initial wave-fields for phase-resolved simulations from either of the following: (i) multiple wave probe records; (ii) ocean surface images from, for example, Scanning Radar Altimeters (SRA), Synthetic Aperture Radars (SAR), or Focused Phased Array Imaging Radars (FOPAIR); and (iii) three-dimensional wave spectral specifications
- Provide a framework for cross-calibration/validation of laboratory and field data and a quantitative assessment of the range of validity and accuracy of phase-averaged wave-prediction models
- Investigate deterministic mechanisms of nonlinear wave dynamics associated with nonlinear wave-wave, wave-current and wave-bottom interactions

APPROACH

An efficient high-order spectral method (HOS) for the phase-resolved simulation of nonlinear surface wave dynamics is extended to practical applications. For data assimilation and specification of the initial conditions for direct phase-resolved time simulations, an effective wave reconstruction scheme based on the multi-level iterative optimization (Wu, Liu & Yue 2000) is applied.

HOS is a pseudo-spectral-based method that can account for nonlinear wave interactions to arbitrary high order (M). The method is extremely efficient as it obtains exponential convergence and linear computational effort with respect to the order (M) and the number of wave modes (N). HOS is an ideal approach for direct simulations of large space-time domain nonlinear evolution of wave-fields. The efficacy of HOS for the study of mechanisms of nonlinear wave dynamics in the presence of atmospheric forcing, long-short waves, finite depth and depth variations and bodies has been well established (e.g. Dommermuth & Yue 1987).

For practical applications, typical physical/computational parameters (for wavelengths of long and short waves λ_l and λ_s respectively, and long wave period T_l) are: computational domain $L^2 \sim O(10^2\lambda_l)^2$, simulation time $T_s \sim O(10^{2\sim3}T_l)$, and $\lambda_l/\lambda_s \sim O(10^{1\sim2})$. With high-performance parallel computing (HPC) capabilities, HOS simulations with these parameters are feasible.

WORK COMPLETED

During the past half year, we focused on the improvement of the efficiency and robustness of HOS and the wave reconstruction scheme and test/validation of HOS computations on distributed-memory parallel platforms (IBM SP3). Specifically, the main work completed includes:

- Development of a highly-efficient parallelized HOS for long-time large-scale simulations of nonlinear wave-field evolutions
- Generalization of HOS to more realistic horizontal boundary conditions
- Improvement of efficiency and robustness of the wave reconstruction scheme
- Preliminary HOS simulations of large-scale ocean wave evolution

PRELIMINARY RESULTS

Direct phase-resolved HOS simulations for large-scale ocean wave-field evolutions are performed. Sample simulation results for the nonlinear evolution of a large (synthetic) three-dimensional wave-field are shown in figures 1-3. These results demonstrate the capacity of our large-scale phase-resolved simulations.

For the results in figures 1-3, the initial wave-field is generated from a three-dimensional directional wave spectrum with winter storm spreading in the Gulf of Mexico (Cornett & Miles 1990). JONSWAP spectrum with a significant wave height of *12* m, a peak period of *15* s, and the width factor of the enhanced peak $\gamma=2.0$ is used. In the HOS simulation, we consider a square wave-field with a side length of $L=5$ km, use $N=1024\times1024$ wave modes, and include the third-order ($M=3$) wave nonlinearity. The shortest wave in the wave-field has a wavelength of $\lambda_s=25$ m (which is about *1/15* of the peak wavelength). The evolution of the wave-field is simulated for *20* minutes (*80* peak periods), which takes about *10* CPU hours on IBM SP3 (with *32* processors).

Figure 1 displays the (instantaneous) free-surface wave pattern at the initial time. The free-surface pattern of the nonlinear wave-field after *19* minutes of evolution is shown in figure 2. Figure 3 plots the time variation of the free surface elevation at two distant locations in the wave-field (marked as A and B in figures 1 and 2) during the nonlinear evolution of the wave-field. Through spectral analyses of these results, we can identify the evolution behavior of the wave-field.

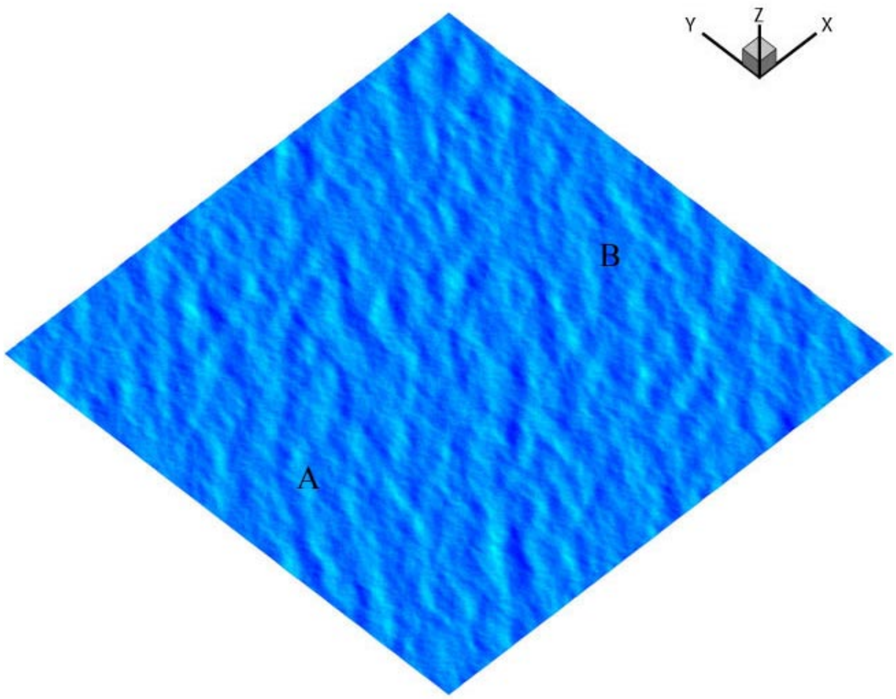

Figure 1. The instantaneous free-surface pattern of the three-dimensional directional ocean wave-field at the initial time.

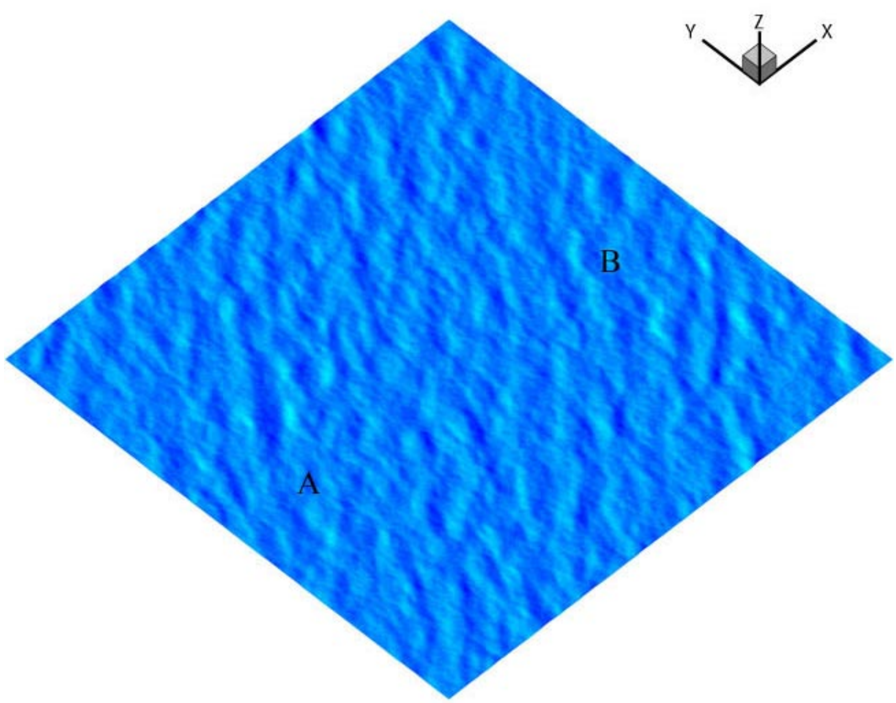

Figure 2. The instantaneous free-surface pattern of the three-dimensional directional ocean wave-field after 19 minutes evolution.

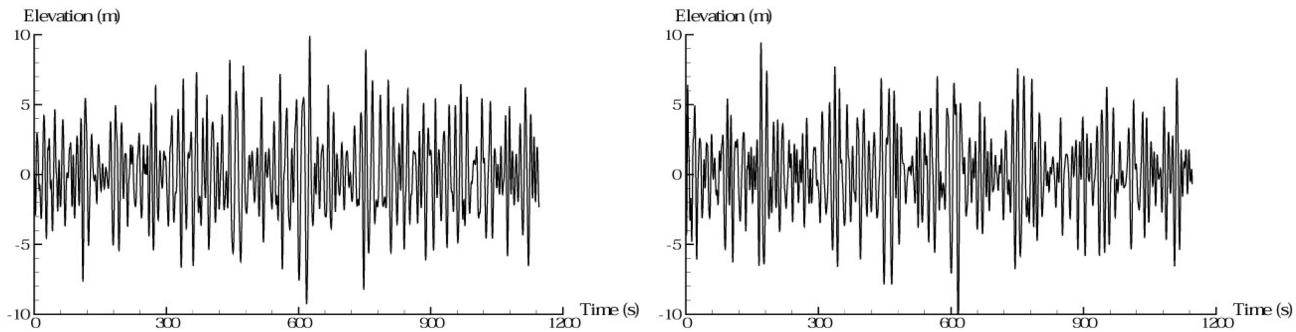

Figure 3: The time variations of the free-surface elevation at positions A (left) and B (right) during the nonlinear evolution of the three-dimensional directional ocean wave-field.

IMPACT/APPLICATION

The present work is a first step toward direct computational prediction of realistic ocean wave-field evolutions without phase-average approximations. It can provide a framework for cross-calibration/validation of laboratory and field data and a quantitative assessment of the range of validity and accuracy of phase-averaged wave-prediction models. It will also be invaluable to improving our understanding and interpretation of remotely-sensed sea surface images.

ON-GOING WORK

The short-term objectives for the year FY2001 are to:

- Generalize HOS for large-scale nonlinear ocean wave evolutions to include more realistic effects such as variable current and bottom topography
- Obtain quantitative comparisons to the phase-average model predictions
- Perform long-time/large-scale HOS simulations of ocean wave evolutions based on wave elevation SAR/SRA data and sea surface velocity FOPAIR data
- Investigate the mechanism of wave focusing associated with nonlinear wave interaction with variable current

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